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Magnetic resonance imaging for in vivo assessment of three-dimensional patellar tracking

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Abstract

We have developed a non-invasive measurement technique which can ultimately be used to quantify three-dimensional patellar kinematics of human subjects for a range of static positions of loaded flexion and assessed its accuracy. Knee models obtained by segmenting and reconstructing one high-resolution scan of the knee were registered to bone outlines obtained by segmenting fast, low-resolution scans of the knee in static loaded flexion. We compared patellar tracking measurements made using the new method to measurements made using Roentgen stereophotogrammetric analysis in three cadaver knee specimens loaded through a range of flexion in a test rig. The error in patellar spin and tilt measurements was less than 1.02° and the error in lateral patellar shift was 0.88 mm. Sagittal plane scans provided more accurate final measurements of patellar spin and tilt, whereas axial plane scans provided more accurate measurements of lateral translation and patellar flexion. Halving the number of slices did not increase measurement error significantly, which suggests that scan times can be reduced without reducing accuracy significantly. The method is particularly useful for multiple measurements on the same subject because the high-resolution bone-models need only be created once; thus, the potential variability in coordinate axes assignment and model segmentation during subsequent measurements is removed.

Keywords: Knee; Patella; Kinematics; MRI; Biomechanics; Accuracy; Tracking; Patellofemoral joint

1. Introduction

Patellofemoral disorders are prevalent and serious, and many are associated with mechanical abnormalities. In a survey of people aged 25–74, 6.5% reported having experienced at least one episode of knee pain that persisted for more than 2 weeks, making it second only to neck and back as a site of pain (Praemer et al., 1992). Anterior knee pain is often associated with the eventual degeneration of the articular cartilage, which frequently leads to long-term disability (Fulkerson, 1997; Scuderi, 1995). The patella was involved in over 50% of knee osteoarthritis cases (Felson, 1990). While both anterior knee pain and arthritis are thought to have mechanical causes, these causes have not been identified because methods for assessing patellofemoral mechanics in vivo have not been available until recently.

Previous ex vivo studies of patellofemoral kinematics have revealed much about the joint, but application of these findings to patients is limited. Three-dimensional

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(3D) patellofemoral kinematics have been measured in cadaver specimens loaded in mechanical rigs using a number of invasive techniques (Heegaard et al., 1994; van Kampen and Huiskes, 1990; Ahmed et al., 1999; Hsu et al., 1996). A key limitation of these ex vivo studies is that the simplified loading applied to the cadaver specimens is unlikely to simulate the in vivo loading conditions responsible for patellofemoral pain and cartilage degeneration. Morphological adaptations due to the disease process or the healing process and mechanical links to clinical symptoms such as pain and progressive cartilage degeneration cannot be studied in cadavers.

Most in vivo studies of patellar tracking have derived 2D kinematic measurements using contemporary imaging techniques. Generally, 2D images are taken of patellar position under static, and more recently dynamic (e.g., Muhle et al., 1999; Shellock et al., 1993), conditions with imaging tools such as computed tomography (CT) and magnetic resonance imaging (MRI). Patellar kinematics are usually described using 2D angles, such as the congruence angle (Muhle et al., 1999) and 2D translations or ratios, such as lateral patellar displacement (Muhle et al., 1999). It is difficult to quantify the relationship between these 2D parameters and their 3D counterparts because measurements will depend on slice position and orientation as well as patient positioning. The accuracy of these kinematic measurements is often unknown.

A few techniques have been developed to assess 3D patellar tracking in vivo. In one approach, patellofemoral kinematics were measured with markers fixed to pins driven into intracortical bone (Koh et al., 1992; Lafortune, 1984). While these measurements were accurate, the protocol is far too invasive to be practical on a larger scale. More recent techniques have employed cine-phase contrast (cine-PC) or fast-phase contrast (fast-PC) MRI (e.g., Rebmann and Sheehan, 2003) to assess 3D tracking of the loaded patellofemoral joint. Although promising, these techniques have limitations. Most notably, subjects must flex their knees through approximately 100 continuous cycles (2:48 min), limiting the magnitude of load that can be applied during testing and the applicability of this technique with subjects suffering from anterior knee pain. Motion artefacts may also be present in the images due to inconsistent movement and pulsatile motion within the imaging plane.

We have developed a new technique to measure 3D patellar kinematics in vivo that uses registration of high-resolution and low-resolution segmented magnetic resonance images. Our objective was to describe the technique and answer the following specific research questions: (1) How accurately does the method measure patellar tracking? (2) How do slice number and direction affect the method's accuracy?

2. Material and methods

Two right and one left fresh human cadaver knee specimens [all Caucasian males: age, 49.7 (26.6) years (mean (standard deviation)); height, 1.76 (0.07) m; weight, 59.74 (1.31) kg], including all tissues 45 cm proximal and distal to the joint line, were obtained from an anatomical tissue bank (ScienceCare Anatomical, Phoenix, AZ, USA). The specimens were stored frozen (at −70 °C) between experiments and thawed in air (20 h at 20 °C) prior to all preparation or testing. To prepare the cadavers for testing, the quadriceps tendon was dissected out of the musculature and a 4.8 mm diameter nylon cord was sutured to the tendon. The vastus medialis and vastus lateralis were then resected, leaving approximately 12–15 cm of exposed bone at the distal end of the femur. The exposed proximal femur was centred and rigidly fixed in a potting base made from a plastic (PVC) tube using dental cement (A-Tech Buff Special Fast Precision Stone, Ash Temple Ltd.). The potting base allowed the knees to be mounted on a loading rig (Fig. 1), on which the femur was held in a fixed, horizontal position and the tibia was allowed to hang freely. The specimens were sprayed frequently with saline solution through the course of all experiments to ensure that they did not dry out.

The knee was flexed and extended while in the rig by shortening and lengthening the cord attached to the extensor mechanism of the quadriceps tendon. The cord length could be fixed, allowing the knee to be held at static positions of flexion. The quadriceps force at each position was dictated by the weight of the tibial shank (different for each specimen) and the knee flexion angle. Thus, quadriceps loading as a function of flexion angle was consistent from experiment to experiment for each specimen (although it was not measured).

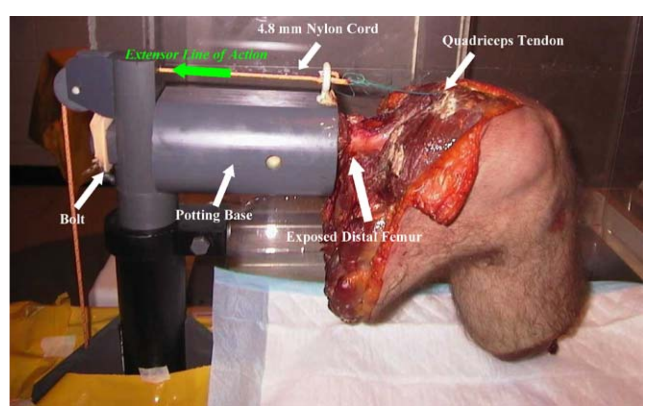

Fig. 1. MR compatible loading rig, which held the femur of the cadaver knee in a fixed and horizontal position, allowing the tibia to hang freely. The knee was flexed and extended by shortening and lengthening the cord sutured to the quadriceps tendon.